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The consequence of a limited-capacity short-term memory on repeated visual search

Christof Körner Margit Höfler Anja Ischebeck

University of Graz

Iain D. Gilchrist

University of Bristol

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Christof Körner, Department of Psychology, University of Graz, Graz, Austria; Margit Höfler, Department of Psychology, University of Graz, Graz, Austria; Anja Ischebeck, Department of Psychology, University of Graz, Graz, Austria; Iain D. Gilchrist, School of Experimental Psychology, University of Bristol, Bristol, UK. The authors report no conflicts of interest.

Correspondence concerning this article should be addressed to Christof Körner, Department of Psychology, University of Graz, Universitätsplatz 2/III, A-8010 Graz, Austria. E-mail: christof.koerner@uni-graz.at

Abstract

When participants search the same letter display repeatedly for different targets we might expect performance to improve on each subsequent search as they memorise characteristics of the display. However, here we find that search performance improved from a first search to a second search but not for a third search of the same display. This is predicted by a simple model that supports search with only a limited capacity short-term memory for items in the display. To support this model we show that a short-term memory recency effect is present in both the second and the third search. The magnitude of these effects is the same in both searches and as a result there is no additional benefit from the second to the third search.

Keywords: visual search, short-term memory, eye movements

The consequence of a limited-capacity short-term memory on repeated visual search

The following situation is familiar to all of us: We are late for an appointment and search the living room for the car keys. Then we remember that we also need our jacket. This kind of visual search includes two consecutive searches for two different target objects (the keys and then the jacket) among the same distractor objects in the same environment. This situation is particularly interesting for the investigation of memory processes: We would expect that, if information about the objects in the environment is retained from the first search, this may speed up search for the next target. That is, we would expect to find the jacket faster than the car keys because we have already inspected the scene once and may have even seen the jacket in the first search.

Recent research has indicated that participants benefit from previous searches when they have to search the same display repeatedly (e.g., Hout & Goldinger, 2010, Hollingworth, 2012; see, however, Kunar, Flusberg & Wolfe, 2008; Wolfe, Klempen & Dahlen, 2000). For instance, Solman and Smilek (2010; see also Solman & Smilek, 2012) analyzed the eye movements of participants and showed that search performance improved if participants searched the same display several times consecutively. Similarly, Hout and Goldinger (2010; see also Hout & Goldinger, 2012) showed that incidental learning of object identities and spatial layouts enhanced the performance across multiple searches.

We have demonstrated that short-term memory (STM) processes facilitate this kind of search. For instance, in Körner and Gilchrist (2007) we investigated how long it took to find a target in the second of two consecutive searches depending on when it was fixated during the first one. We had participants perform a visual search task in the same letter display twice. At the beginning of the first search, a target letter was presented to the participants. After a manual absent/present response to that target, a further (second) target was announced and the participants were asked to search for it in the same display. Crucially, if this second target was present in the display and if it was one of the distractor letters that had been inspected during the previous search, we showed a target recency effect after the first search: the more recently an item was inspected in the previous search the faster it was found in the subsequent search. This effect was limited to four or five most recently inspected items and was also reflected in an overall search-time benefit in the second search: the second search was significantly faster than the first search (see also Howard, Pharaon, Körner, Smith, & Gilchrist, 2011, for an analogous experiment involving repeated search among real objects in three-dimensional space). In subsequent work, we showed that the recency effect and the resulting search-time benefit for the second search are robust to temporal decay and interfering information introduced between the two searches and that they rely on both the identity and the location information of the items (Höfler, Gilchrist, & Körner, 2014).

The recency effect that we have identified in our previous research indicates that a capacity-limited STM supports search when the same display is searched twice. After a search is completed, about four to five most recently inspected items are stored in STM and this information is used to guide the upcoming search back to these items if the target is among them (target guidance). The same information seems to be used to guide search away from them if the target is not among them (distractor avoidance). This latter mechanism results in guidance towards new (uninspected) items (Höfler, Gilchrist, & Körner, 2015). In general, the guidance by memory results in shorter search times for the second search.

We now return to the introductory example. Imagine we are late for an appointment and search the living room for the car keys, then for the jacket and finally we decide that we also need a scarf. Intuitively, one would expect that search improves further with every repeated search of the same display. All things being equal, the first search should be slower than the second and the second slower than the third. The literature cited above on multiple repetitions of a search in the same display seems to suggest just that.

However, here we argue that there will be no such further improvement if the display is searched for another (third) time. In particular, we reason that the response times should *not* improve in the third search with regard to the second search while the most recently inspected items are still found faster. The logic of our reasoning is as follows. During the first search, the (previously empty) STM buffer becomes filled with inspected items. At the end of the first search it contains, due to its limited capacity, only about four to five recently inspected items. If the target of the second search is among those items, search is guided towards it and it is found faster (target guidance). The resulting target recency effect is also reflected in a search benefit such that the second search is faster than the first search. If the target of the second search is not among the items stored in the STM buffer its contents can still be used to guide search away from those items (distractor avoidance), also resulting in a search benefit for the second search. At the beginning of the second search, the STM buffer is filled with item information which will be successively overwritten by new information gathered during that search. Thus, at the beginning of the third search, again only the four to five most recent items of the previous (second) search will be available in the buffer. Consequently, information is always restricted to the limited amount currently stored in STM. We have implemented the idea of target guidance and distractor avoidance, based on the information available in STM in a simple computational model described below. On this basis, we predict that search performance (i.e., the response time, number of fixations) in the third search should not improve beyond the level of the second search. However, we still expect a *memory benefit* (i.e., a target-recency effect) in the third search for the most recently inspected items of the second search just as we expect a memory benefit in the second search for the recent items of the first search. This benefit should always be of the same magnitude and not accrue across searches.

Model

In this modelling exercise, we have considered only the case of target-present searches. For target present searches, when the search process encounters the target this event constitutes a clear criterion for terminating the search. However, it is less clear what factors influence the termination of search when a target is absent. This case would need additional assumptions about the stopping rule. To keep the model simple, we have restricted ourselves to the target present case. The following description focuses on the structural aspects of the model. A flow chart that highlights procedural aspects can be found in Supplementary Figure S1.

In our model, a limited-capacity memory buffer operates according to a first-in first-out (FIFO) principle (cf. Philipps, Shiffrin & Atkinson, 1967; Kool, Conway & Turk-Browne, 2014), a term borrowed from computer science (e.g. Knuth, 1997, p. 204). In general, at the beginning of a search the buffer is empty. Each time attention visits an item (i.e. it is fixated) that item enters the buffer and attention moves on to the next item until the target is found. Critically, the capacity of this buffer is limited to N items. If the capacity limit is reached before the search is terminated then information must be deleted from the buffer to make room for new incoming information. We propose that the item that first entered the buffer (as it is the one with the longest residence time) would also be the first one to exit the buffer. That is, when the buffer is filled to capacity it will always contain information of only the N most recent items.

The model involves the two mechanisms that we have identified in our work with a single repeated search. These mechanisms use the information stored in the FIFO buffer. There is a mechanism that guides search away from distractors (distractor avoidance) and a mechanisms that guides search towards a target (target guidance) if the respective items are present in the buffer. Specifically, we assume that, at the beginning of a repeated search trial, the probability of fixating an item is identical for all items in the display. With each single fixation, the newly selected item enters the buffer at position 1, i.e. this item has the shortest residence time, and the item with the longest residence time leaves the buffer, if it is filled to the capacity limit N. The probability of fixating an item is then updated depending on its presence in the buffer. If an item is in the buffer and it is a distractor, its probability of being fixated is reduced. In contrast, if the item is a target, its fixation probability is increased.

The example outlined above is the simplest case of an all-or-none model. It is possible to develop a more complex model in which the memory strength depends on the position in the buffer (residence time). However, such a model is more complex than the simple all-or-none model and we have found the simple model to be sufficient to capture the basic effects observed in our previous experiments with a single repetition. Assume the buffer can hold $N = 5$ items and is filled to capacity. In an all-or-none model all the fixation probabilities of items currently resident in the buffer are treated equally, irrespective of the position in the buffer. When a new item is fixated it enters the buffer at position 1 and the oldest item (at buffer position 5) leaves it. All the remaining items are shifted one position down in the buffer. If the new item is a distractor then the probability of fixating this and the other 4 items in the buffer (except for the target) is reduced by the same amount. As a result, it becomes unlikely that these items are refixated. Reciprocally, the probability of fixating items which are not in the buffer increases. As a consequence, search is guided away from (old) items currently held in the buffer and towards new items (distractor avoidance). Likewise, if a target is in the buffer its fixation probability is increased irrespective of its position in the buffer (target guidance). That is, as long as an item is in the buffer its fixation probability is increased (target) or decreased (distractors) by the same amount.

Figure 1 about here

We simulated a FIFO model with the following settings. (a) Fixation probabilities of all items resident in the buffer are reduced/increased by the same amount (all-or-none). (b) Fixation probability of a target resident in the buffer is increased by the same amount as the probability of distractors is reduced. In our simulations, we chose a display size of 10 items which is typical for our previous search experiments. We varied the number of items *N* that the buffer can hold (buffer capacity) between 0 and 9 memory slots. The former corresponds to a memoryless search (see Gilchrist and Harvey, 2000). For each buffer capacity we simulated search performance, that is we counted the number of fixations necessary to find the target in the display, and thus to terminate search, for three consecutive searches. To obtain stable predictions, we ran 100,000 simulated trials per buffer size.

Figure 1A shows the simulated number of fixations to the target for Searches 1 – 3 depending on buffer capacity. For a capacity of zero the model requires 10 fixations to terminate search. This was to be expected for a memoryless search in a 10-item display. As buffer capacity increases the simulated number of fixations decreases for all searches. In Search 1 the target is found after approximately 6 fixations at a capacity of nine. For Search 2 the number of fixations decreases faster, and a benefit with regard to Search 1emerges for capacities greater than 3; this benefit increases, as the capacity increases. The curve for Search 3 is very similar to Search 2. Only for large buffer capacities is the simulated number of fixations further reduced, at best by about 0.5 fixations. In the Discussion, we will come back to this difference.

Figure 1B shows the number of fixations for Search 2 depending on target recency for selected buffer capacities. At capacity zero there was no recency effect and simulated search performance was memoryless, i.e. it was always at 10 fixations. As capacity increased so did search performance, and a recency effect emerged which was particularly pronounced for capacities of 4 to 6 items. This is the capacity range that we have observed in our previous experiments with a single repetition. When capacity was further increased, performance also increased further. However, the recency effect vanished. Thus, for medium buffer capacities our model captures the shape of the basic recency effect obtained in earlier experiments with a single repetition. Crucially, the pattern of the recency curves for Search 3 (Figure (1C) was very similar to Search 2. We will come back to these observations in the Discussion.

Finally, Figure 1D summarizes the model simulations regarding recency and three consecutive searches for a medium buffer capacity of $N = 5$ items. The number of simulated fixations until target fixation, and thus the shape of the recency curves, are virtually identical for Searches 2 and 3, yet they do not reach the Search 1 baseline. We will return to this point in the Discussion. To summarize, our simulations predict that search performance in the third search should not improve beyond the level of the second search if a STM buffer with a capacity of approximately 5 items supports search. However, we still expect a target-recency effect in the third search just as we expect a benefit in the second search for the recent items of the first search. This benefit is expected to be of the same magnitude and not to accrue across searches.

Experiment

Method

Design

Participants searched the same 10-letter display three times for different target letters. In each of the three searches, the target was present on half the trials and absent on the remainder. As a result there were eight search conditions in total; absent-absent-absent (AAA); absent-absent-present (AAP); absent-present-absent (APA); absent-present-present (APP); present-absent-absent (PAA); present-absent-present (PAP); present-present-absent (PPA); and present-present-present (PPP). We recorded participants' manual responses and their eye movements.

Participants

Twelve students (10 female) from the Department of Psychology, University of Graz, participated for course credit. The mean age was 21.3 years (range 18 to 29). All participants had normal or corrected-to-normal vision. They all gave informed consent. The experiment was approved by the local ethics committee.

Apparatus

We recorded two-dimensional eye movements using an EyeLink II eye tracker (SR Research, Canada). We recorded from the eye that produced the best spatial resolution (typically better than 0.30°) at a sampling rate of 500 Hz. Displays were presented on a 21-inch monitor with a resolution of 1,152 × 864 pixels and a refresh rate of 75 Hz. In order to minimize head movements, a chin rest was used. The software for stimulus presentation and data collection was custom-written in C++.

Stimuli and procedure

Stimuli were presented in white on a black background (see also Körner & Gilchrist, 2007). In each trial we displayed ten upper case letters which subtended 0.32° at the viewing distance of 63 cm. A white circle surrounded each letter. The outer diameter of the circle was 0.9° and the circle was 0.18° thick (see Figure 2). The letters were sampled randomly from the letters A, E, F, G, H, K, M, O, R, S, W, X, Z. The circles around the letter reduced the ability to identify the letter without fixation (c.f. Bouma, 1970) and provided a clear saccade target.

Figure 2 about here

The ten letters were positioned at the intersections of an imaginary 6 × 6 grid. The size of a grid cell was 3.6°. The letter position deviated randomly from the intersection by ± 0.23° both in horizontal and vertical direction. The whole viewing area subtended 21.6° × 21.6°.

At the beginning of each trial, a fixation disc was presented at a position chosen randomly from the locations where a letter would appear in the search display. When fixation was registered, a placeholder display was presented. It was identical to the search display except that each letter was replaced by the hash symbol (#). After 500 ms the placeholder display was replaced by the search display. Simultaneously, the first target letter was announced through loudspeakers placed to the left and the right of the display monitor. If the target was present, the Euclidean distance between the fixation disc and the target was approximately 10.8°. As soon as the participant pressed a button in response to the first target the second target letter was announced. If Search 2 was a target-present search, the target was selected as follows (see also Höfler et al., 2014): Each fixation of Search 1 was assigned to an item, using a minimal (Euclidean) distance criterion. To define the recency position for each fixated item, the scan-path was reversed (i.e., the last fixated item was assigned a recency position of 0 and the penultimate item a recency position of 1 etc.) and a target was chosen from these fixated items with the objective that each recency position was selected equally often during a block of trials. In addition, it was ensured that the target was in a distance of about 10.8° relative to the last fixation searching through all recency positions. If there was no suitable item found, the process was repeated by relaxing the distance criterion to 10.8° ± 3.6°. If a target could not be determined given these constraints or if the computed target was the same as the Search 1 target, a target at a desired distance, regardless of whether this item had been fixated or not, was chosen from the entire set of items present in the display (distance target). If a target could still not be determined, it was chosen randomly from the whole set (random target).

When the participant responded to the second target, a third target letter was announced. If this target was present, it was chosen the same way as in Search 2. When the participant responded to the third target the display was cleared. Participants were instructed to press the right button on a response box for a target-present response and the left button for an absent response; they were also told to respond as quickly and as accurately as possible. The sequence of trials within a block was chosen randomly for each participant. Each subject participated in eight blocks of 64 trials. Four blocks were conducted per session, and the two sessions were conducted on two different days. A session lasted approximately 70 min.

Results

Manual responses

We collected data from 6,144 trials (12 subjects × 512 trials). We excluded 434 trials (7.1%) in which participants provided the wrong response in any of the three searches of a trial. The average error rate ranged from 2.7% to 12.9% between participants and from 1.2% (condition AAA) to 13.9% (condition PPP) between conditions.

Average manual correct response times (RTs) for the three searches are presented in Figure 3, separately for target absent and present trials. To investigate search time benefits due to the repetition, we computed the RT differences between consecutive search pairs on an individual level (i.e., Search 1 minus Search 2 and Search 2 minus Search 3) separately for target present and absent trials. A 2 (search pair: Search 1 - Search 2 vs. Search 2 - Search 3) × 2 (target presence: present vs. absent) ANOVA for repeated measures showed a main effect of search pair, $F(1, 11) = 24.13$, $p < .001$, $\eta_p^2 = .69$ and a main effect of target presence, $F(1, 11) = 9.15$, $p = .012$, $\eta_p^2 = .45$, but no interaction, $F < 1$. Importantly the difference between Search 1 and Search 2 (averaged across target presence) was significant ($M = 222.0$ ms, 95% CI [158.0, 286.0]; see Cousineau, 2005; Morey, 2008) while the difference between Search 2 and Search 3 was negligible ($M = -1.3$ ms, 95% CI [-42.2, 39.5]). These findings clearly demonstrate a benefit in Search 2 from previous exposure to the display in Search 1 but no additional improvement in performance in Search 3.

Figure 3 about here

Eye movements

Each fixation recorded by the eye tracker was allocated to an item using a minimal distance criterion, i.e., the fixated item was defined as the item that had the smallest Euclidean distance from the actual position of the gaze at that time. We then counted the number of fixations (without removing any possible outliers) and obtained the same pattern as depicted for RTs in Figure 3. For target present searches, Search 1 lasted for 5.8 fixations (SD = 0.5), Search 2 lasted 5.2 fixations (SD = 0.7), and Search 3 lasted 5.0 fixations (SD =0.6). We repeated the 2 (search pair: Search 1 - Search 2 vs. Search 2 - Search 3) × 2 (target presence: present vs. absent) ANOVA conducted for the RTs with the number of fixations per search. This again produced a main effect of search pair, $F(1, 11) = 4.98$, $p = .047$, $\eta_p^2 = .31$ and a main effect of target presence, $F(1, 11) = 9.46$, $p = .011$, $\eta_p^2 = .46$, but no interaction, $F < 1$. This was to be expected as manual RTs and the number of fixations are closely linked in serial visual search (Williams et al., 1997). These results therefore corroborate the RT results using a fixation measure.

To investigate whether recently inspected items of a previous search are found faster in a subsequent search we conducted two separate recency analyses for each pair of consecutive searches (i.e., Search 1 vs. Search 2 and Search 2 vs. Search 3, respectively). We counted the number of fixations necessary to find a target in Search 2 (Search 3) depending on when it was last fixated in Search 1 (Search 2). All trials in which a random target had been selected in Search 2 (9.4 % of the trials) or Search 3 (9.0 %, see Procedure) were excluded from this analysis. To increase statistical power, we pooled data from Recency Positions 8 and 9. Due to the online selection of the subsequent target (see Procedure) the minimum number of observations per recency position and participant was 19 (Search 2) and 17 (Search 3). Figure 4 shows the recency curves for Search 2 (target present trials) with respect to Search 1 (search conditions APA, APP, PPA, and PPP) and for Search 3 (target present trials) with respect to

Search 2 (search conditions AAP, APP, PAP, and PPP).

Figure 4 about here

We carried out a 2 × 8 repeated measures ANOVA with search (Search 2 vs. Search 3) and Recency Position (1 to 8) as factors. There was no effect of search, $F(1, 11) = 1.92$, $p = .19$, but a reliable effect of recency, $F(1.57, 17.23) = 10.04$, $p = .002$, $\eta_p^2 = .48$. The interaction was not significant, $F < 1$.

To quantify the recency effect, we compared the number of fixations until the first target fixation for each recency position with the number of fixations necessary to find the Search 1 target ($M = 5.8$, $SD = 0.5$) as a baseline. A series of *t*-tests showed that, in Search 2, performance at Recency Positions 1, 2 and 4 was significantly better than Search 1 baseline (Bonferroni-Holm corrected; $p < .05$ in each case; effect size *d* ranging between 1.08 and 1.24). Recency Position 3 just failed to reach significance (p =. 06). In Search 3, performance at Recency Positions 1 to 4 was better than baseline (Bonferroni-Holm corrected; $p < .05$ in each case; effect size *d* ranging between 1.38 and 2.32)[1]. Together, these results indicate that there were target recency effects of similar magnitude for Search 2 with regard to Search 1 and for Search 3 with regard to Search 2.

To test whether the recency curves of Search 2 and 3 had comparable shapes we fitted a linear function for each subject where the number of fixations depends on the (natural) logarithm of the recency position and compared the resulting multiplicative and additive parameters between Search 2 and Search 3. Two one-way repeated measures ANOVAs, one for each parameter, showed no difference in the form of the fitted recency curves between searches, $F < 1$ in both cases.

Figure 5 about here

The previous analyses of manual RTs and number of fixations per search revealed that there was a benefit in Search 2 and Search 3 compared to Search 1 when a target was present in those searches. This corroborates the idea of target guidance, as implemented in our model. However, there also seems to be a benefit if the target is absent in a search. Such a benefit can only result, if we assume that search can also be guided by memory for distractors (distractor avoidance). For example, Figure 3 indicates that there was a decrease in RT from Search 1 to Search 2 and Search 3 when targets were absent. To investigate this benefit, we conducted a recency analysis for the 759 correct trials from the AAA search condition as follows. We counted how often a distractor was fixated in Search 2 depending on when it was last fixated in Search 1 and then carried out the same analysis for how often a distractor was fixated in Search 3 depending on when it was last fixated in Search 2. This frequency divided by the total number of searches yielded the probability of a distractor being fixated depending on its recency in the previous search. As can be seen in Figure 5, the probability of a distractor being (re-) fixated in the current search when it had just yet been fixated in the previous search (Recency Position 1) is somewhat higher than 0.5 and quickly rises to the maximum for higher recency positions. Moreover, the recency curves for Search 2 and Search 3 are almost identical. Participants are using their memory to avoid recently fixated distractors from the previous search. This was confirmed by a 2 × 6 repeated measures ANOVA with search (Search 2 vs. Search 3) and recency position (1 to 6) as factors. There was no effect of search, $F < 1$, a reliable effect of recency, $F(1, 11) = 28.90$, $p < .01$, $\eta_p^2 = .72$, and no interaction, $F < 1$.

Discussion

When we search the same display repeatedly, the intuition would be that search performance improves with every repetition. Contrary to this expectation we have shown in the current experiment that, although a second search in the same display is faster and requires fewer fixations than a first search, no further improvement occurs in a further (third) search. We argued that this "non-improvement" after the second search is due to a capacity limit of the memory processes involved in search. In particular, we have shown that recently inspected items are stored in STM after each search and if one of these items becomes the target in the subsequent search, it is found faster than a less recently inspected one (target guidance). Further analyses revealed that the magnitude and the form of this target-recency effect was the same for the second search regarding the first search and for the third search regarding the second search. Thus, participants always benefited from a previous search to the same extent. However, this benefit was reflected in an improved search performance (i.e. faster response times and fewer fixations) only after the first search because this search represented a baseline search, without any previous experience from the display and hence, without any memory benefit.

We also found a benefit for subsequent searches without a target. An analysis of fixation probabilities showed that the likelihood of fixating a distractor also depended on its recency in the previous search (distractor avoidance). Again, this effect was of the same order for Search 2 and Search 3 and did not increase across searches. This finding further underlines the assumption of a limited-capacity system that supports search. Only recent distractors from a previous search are less likely to be revisited in a current search when the target is absent.

These recency effects are in line with previous research that has used more direct methods of probing distractor memory. For instance, Beck, Peterson, Boot, Vomela and Kramer (2006) interrupted the search and had participants decide which of two presented objects had been present at a previously searched location. The results showed that participants performed above chance for the three most recently fixated items and that performance decreased with the recency of the object. Zelinsky and Loschky (2005) had participants freely inspect objects in a scene before the display was replaced by a spatial probe and participants were asked to identify the object that was present at the probed location. Again, the results showed a recency effect (in terms of recognition accuracy) for the three most recently inspected objects.

Is such memory in visual search more of a spatial nature or is information about identity of objects stored as well? Previous research which studies more typical single searches has shown that spatial memory is crucial for efficient search. For instance, Beck, Peterson and Vomela (2006) demonstrated that a change of location but not of identity of previously fixated objects during a single search disrupted the search process. This suggests that location information was at least partially retained during search but not necessarily the identity of the object at that location. This is consistent with the idea of the memory being used to tag locations as visited but without storing the target identity. Similarly, experiments using a secondary memory task showed that search efficiency only decreased if participants' spatial working memory was loaded during search but not if participants' non-spatial memory was loaded (Oh & Kim, 2004; Woodman & Luck, 2004). However, in the present repeated search experiment, location memory *and* identity information was important in order to maintain information across searches. If the identity of the distractors were not stored then we would not see the benefit when that previously stored distractor subsequently became the target. Thus, for repeated search task, participants have to remember the locations they have inspected during the previous search and the identity of the letter at this location in order to find recently inspected items faster in the subsequent search.

In order to explain the pattern of results from our experiment we implemented a FIFO principle in a model of repeated search in which fixation probabilities of items are dynamically updated depending on their presence in a capacity-limited buffer. Fixation probabilities of distractors stored in the buffer are decreased with the result that the search process avoids such items and is guided towards (new) items which are not currently in the buffer. Conversely, the fixation probability of a target stored in the buffer is increased, which guides search towards it. In our simulations we have shown that a parsimonious version of such a model is able to predict the pattern of the data obtained in the current experiment on a qualitative level. In particular, we demonstrated a search benefit from Search 1 to Search 2 which did not further increase with an additional search. More importantly, our model predicted a recency effect. If the target of the subsequent search was more recent with respect to the previous one, it was found faster. Critically, this recency effect was identical for Search 2 and Search 3, as predicted by our simulations.

For the sake of simplicity and parsimony, we made a few assumptions in the implementation of the model which are worth discussing. First, we assumed an all-or-none principle. That is, fixation probabilities of items resident in the buffer were updated after each fixation irrespective of residence time. Only the presence or absence of an item in the buffer determined whether or not its fixation probability was modified by the same amount as the other items. Considering the form of the empirical recency curves this assumption seems counter-intuitive. The recency curves seem to suggest that information decays the longer it stays in the buffer. Yet our simulations demonstrate that a recency effect can emerge without imposing decay on the stored information. The FIFO principle in itself may produce the recency effect. If a target is more recent it will stay in the buffer longer before it exits it. This means that a more recent target has a high probability of being fixated repeatedly before it leaves the buffer. Nonetheless, our model framework could be extended without any significant structural change to allow for a systematic decay (linear or otherwise) on the information held in the buffer. The addition of decay to the model is a topic that we will address systematically in future research. A second simplifying assumption was that we set the probability decrease for distractors to be the same as the increase for a target if such items were present in the buffer. This means that the memory representation of previously attended distractors is as good as the representation of the current target. While this may be true with respect to memory – after all the current target in our paradigm is always a recently processed distractor – it is implausible that guidance resulting from distractors is as strong as guidance resulting from a target. The fixation probability analysis for distractors (Figure 5) suggests an impact of distractor avoidance on search that is smaller than the impact of target guidance (Figure 4). Obviously, this is another issue that could be addressed when the model is developed further. Finally, our model currently considers target-present searches only. For modelling the termination of target-absent searches, additional assumptions may be necessary in the future, as we develop a more comprehensive version of the model.

In the simulations we found a somewhat greater search benefit for Search 3 as compared to Search 2 when the buffer capacity was high. Figure 1A demonstrates that a high-capacity buffer leads to shorter searches already in Search 1. Consider, for example, that the target is found after only 3 fixations in Search 1 and Search 2, respectively. For a medium-capacity buffer this means that capacity is exceeded at the beginning of Search 3. However, if buffer capacity is high, there is still storage capacity left to support the new search without sacrificing the memory from previous searches. In such particular circumstances, an additional benefit for Search 3 may actually occur.

Unlike the empirical recency curves (Figure 4), the simulated curves did not reach baseline (Figure 1D). Comparing the simulations with the data, one can also observe that the baseline in the experiment was lower than in the simulations. Thus, it is unclear whether the model underestimates the recency effect or overestimates the baseline, or both. Again, this needs to be addressed in a future version of the model.

Our model – even in its present simple form – allows predictions that we did not test in the current experiment. For example, the model provides a probability distribution on the set of all items that dynamically changes with each single fixation. That is, the model predicts what item will be fixated next. With the current experiment, we focused on the end result of search, that is, on search performance as represented by response times and number of fixations. Our aim here was to test a core property of the model deriving from the FIFO characteristic of the capacity-limited memory buffer, namely the prediction that search performance does not improve beyond a second search. The current experiment provides clear support for this prediction. To test additional properties of the model, specifically designed experiments should be used.

Our results appear to be in conflict with findings that show that search improves with repetition (e.g. Hout & Goldinger, 2010, 2012; Solman & Smilek, 2010, 2012). In these experiments, participants searched the same display dozens of times. The improvement was reflected in decreasing search times for epochs consisting of data pooled across many consecutive searches. We therefore assume that such benefits are the result of long-term memory (LTM) processes. Our findings indicate that LTM processes are not involved when a display is searched only three times. It is left to future research to investigate if and how STM and LTM interact when a display is repeated more frequently.

We have repeatedly demonstrated that a capacity-limited STM supports search when the same display is searched twice (Körner & Gilchrist, 2007; Höfler et al., 2014, 2015). Here we have demonstrated that a simple model of such a memory system is able to capture the basic pattern of our earlier results. More importantly, for the present experiment, this model revealed an important consequence of the capacity limit – such a STM system cannot improve search performance beyond the second search. This means that, although memory processes support repeated search, this support is not always mirrored in a performance benefit.

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References

Beck, M., Peterson, M. S., Boot, W. R., Vomela, M., & Kramer, A. F. (2006). Explicit memory for rejected distractors during visual search. *Visual Cognition, 14*, 150-174. doi:10.1080/13506280500460563

Beck, M., Peterson, M. S., & Vomela, M. (2006). Memory for where, but not for what is used during visual search. *Journal of Experimental Psychology: Human Perception & Performance, 32*, 235–250. doi:10.1037/0096-1523.32.2.235

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature, 226*, 177-178. doi:10.1038/226177a0

Cousineau, D. (2005). Confidence intervals in within-subject designs: a simpler solution to Loftus and Masson's method. *Tutorial in Quantitative Methods for Psychology, 1*, 42-45.

Gilchrist, I. D. & Harvey, M. (2000). Refixation frequency and memory mechanisms in visual search. *Current Biology, 10(19)*, 1209-1212.

Höfler, M., Gilchrist, I. D., & Körner, C. (2014). Searching the same display twice: Properties of short-term memory in repeated search. *Attention, Perception, & Psychophysics, 76*, 335-352. doi: 10.3758/s13414-013-0589-8

Höfler, M., Gilchrist, I. D., & Körner, C. (2015). Guidance toward and away from distractors in repeated visual search. *Journal of Vision, 15*(5), 1-14. doi:10.1167/15.5.12

Hollingworth, A. (2012). Task specificity and the influence of memory on visual search: Comment on Võ and Wolfe (2012). *Journal of Experimental Psychology: Human Perception and Performance, 38,* 1596-1603. doi:10.1037/a0030237

Hout, M. C., & Goldinger, S. D. (2010). Learning in repeated search. *Attention, Perception, & Psychophysics, 72,* 1267-1282. doi:10.3758/APP.72.5.1267

Hout, M. C., & Goldinger, S. D. (2012). Incidental learning speeds visual search by lowering response thresholds, not by improving efficiency: evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance, 38,* 90–112. doi:10.1037/a0023894

Howard, C. J., Pharaon, R. G., Körner, C., Smith, A. D., & Gilchrist, I. D. (2011). Visual search in the real world: Evidence for the formation of distractor representations. *Perception, 40*, 1143–1153. doi:10.1068/p7088

Knuth, D. E. (1997). *The art of computer programming Volume 1* (3rd Ed). Addison-Wesley. Upper Saddle River, NJ.

Kool, W., Conway, A. R. A., & Turk-Browne N. B. (2014). Sequential dynamics in visual short-term memory. *Attention, Perception, & Psychophysics, 76,* 1885-1901. doi:10.3758/s13414-014-0755-7

Körner, C., & Gilchrist, I. D. (2007). Finding a new target in an old display: Evidence for a memory recency effect in visual search. *Psychonomic Bulletin & Review, 14,* 846–851. doi:10.3758/BF03194110

Kunar, M. A., Flusberg, S., & Wolfe, J. M. (2008). The role of memory and restricted context in repeated visual search. *Perception & Psychophysics, 70,* 314-328. doi:10.3758/PP.70.2.314

Morey, R. D. (2008). Confidence intervals from normalized data: A correction to Cousineau (2005). *Reason, 4*(2), 61-64.

Oh, S.-H. & Kim, M.-S. (2004). The role of spatial working memory in visual search efficiency. *Psychonomic Bulletin & Review, 11,* 275–281. doi: 10.3758/BF03196570

Solman, G. J. F., & Smilek, D. (2010). Item-specific location memory in visual search, *Vision Research, 50,* 2430–2438. doi:10.1016/j.visres.2010.09.008

Solman, G. J. F., & Smilek, D. (2012). Memory benefits during visual search depend on difficulty. *Journal of Cognitive Psychology, 24*(6), 689-702. doi:10.1080/20445911.2012.682053

Williams, D.F., Reingold, E.M., Moscovitch, M., & Behrmann, M. (1997). Patterns of eye movements during parallel and serial visual search tasks. *Canadian Journal of Experimental Psychology, 51*, 151 – 164.

Woodman, G. F., & Luck, S. J. (2004). Visual search is slowed when visuospatial working memory is occupied. *Psychonomic Bulletin & Review, 11,* 269–274. doi: 10.3758/BF03196569

Wolfe, J. M., Klempen, N., & Dahlen, K. (2000). Postattentive Vision. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 693–716. doi:10.1037/0096-1523.26.2.693

Zelinsky, G. J., & Loschky, L. C. (2005). Eye movements serialize memory for objects in scenes. *Perception & Psychophysics, 67*, 676–690. doi:10.3758/BF03193524

Footnotes

[1]The recency analysis is based on the correctness of the null hypothesis which states that the number of fixations to find the target in a subsequent search does not differ from the number of fixations in the first search (baseline). In a Bayesian analysis, we directly tested the null hypothesis that the effect (deviation from baseline) is in a small region around the baseline defined by a deviation of ± 0.2 in terms of effect size *d*. We compared the number of fixations for all recency positions and Search 2 and 3 with the baseline from Search 1. For Recency Positions 1 to 4 Bayes factors supporting the null hypothesis ranged between 0.002 and 0.15, indicating no support for the hypothesis that the observed deviation is anywhere close to the baseline region; for Recency Position 5, Bayes factors for the null hypothesis were inconclusive (Search 2: 1.88; Search 3: 0.72). Finally, for Recency Positions 6 to 8, Bayes factors ranged from 5.20 to 6.1, indicating positive support for the null hypothesis.

Figure Captions

Figure 1. Summary of simulation results. (A) Number of simulated fixations until target fixation for Search 1 (solid line without markers), Search 2 (dashed line with markers), and Search 3 (solid line with markers) for varying buffer capacity. (B) Number of simulated fixations until target fixation in Search 2, depending on the target recency in Search 1 for buffer capacities of 0, 5, 6, and 9 (top to bottom). (C) Number of simulated fixations until target fixation in Search 3, depending on the target recency in Search 2 for buffer capacities of 0, 5, 6, and 9 (top to bottom). (D) Number of simulated fixations until target fixation in Search 2 (dashed line) and Search 3 (solid line), depending on the target recency in the previous search. The baseline indicates the mean number of fixations until first target fixation in Search 1.

Figure 2. Sequence of events in a trial.

Figure 3. Mean response times for the three consecutive searches, separately for target-absent and target-present searches. Error bars represent the 95% confidence intervals (Cousineau, 2005; Morey, 2008).

Figure 4. Number of fixations until the first target fixation in Search 2 (dashed line) and Search 3 (solid line), depending on the target recency in the previous search. The baseline indicates the mean number of fixations until first target fixation in Search 1. Search 2 performance was better than baseline for recency positions 1, 2, 4, and Search 3 performance was better than baseline for positions 1 to 4.

Figure 5. Probability for an item to be fixated in Search 2 (dashed line) and Search 3 (solid line) in target-absent searches, depending on its recency in the previous search.

Figure S1. Flow chart for model simulation. (See text for explanation.)

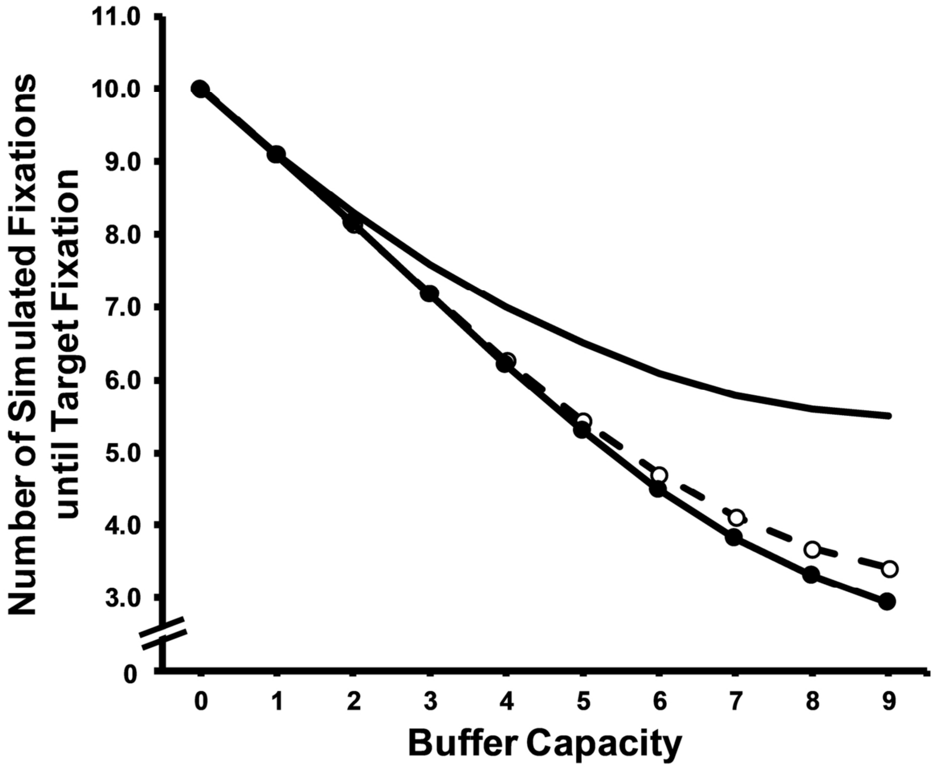


Figure 1. Summary of simulation results. (A) Number of simulated fixations until target fixation for Search 1 (solid line without markers), Search 2 (dashed line with markers), and Search 3 (solid line with markers) for varying buffer capacity.

152x124mm (300 x 300 DPI)

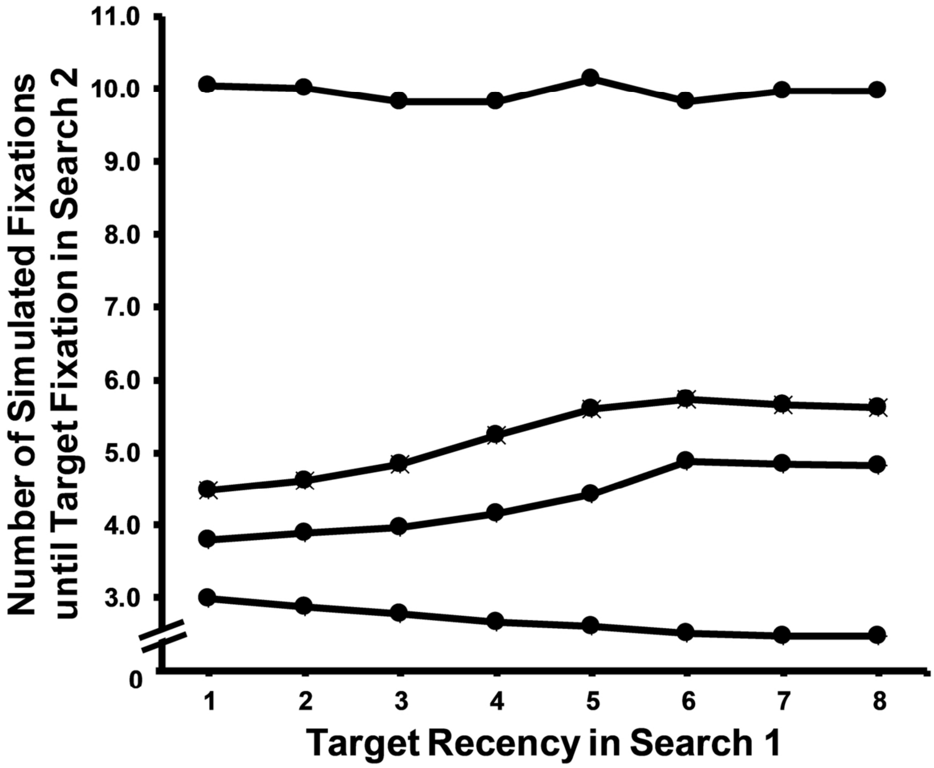


Figure 1. Summary of simulation results. (B) Number of simulated fixations until target fixation in Search 2, depending on the target recency in Search 1 for buffer capacities of 0, 5, 6, and 9 (top to bottom).

152x124mm (300 x 300 DPI)

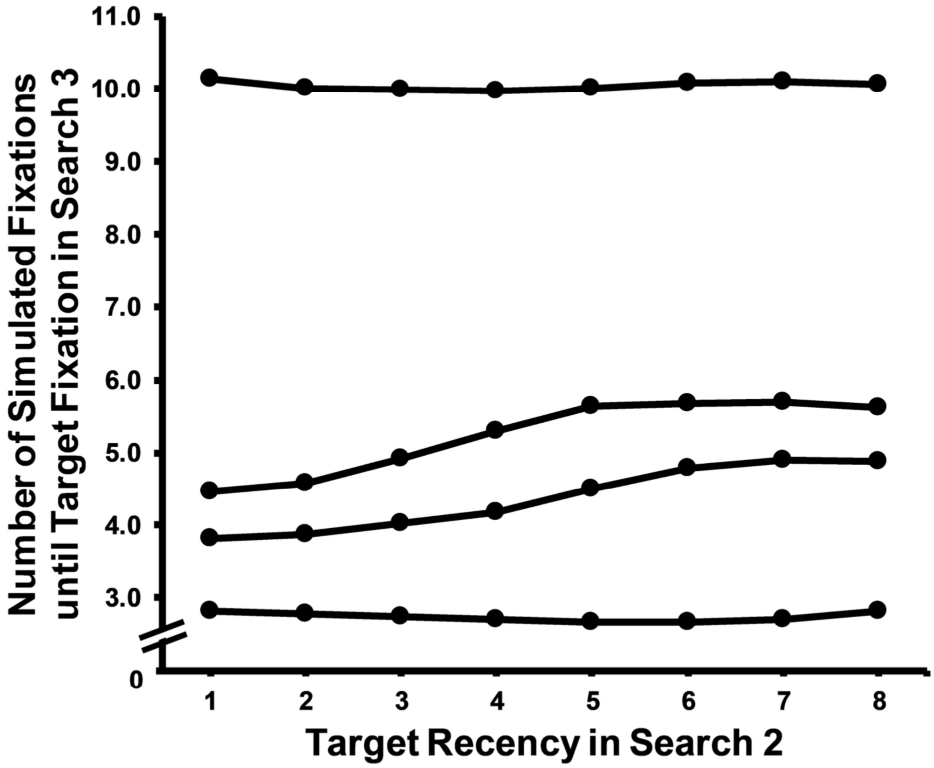


Figure 1. Summary of simulation results. (C) Number of simulated fixations until target fixation in Search 3, depending on the target recency in Search 2 for buffer capacities of 0, 5, 6, and 9 (top to bottom).

152x124mm (300 x 300 DPI)

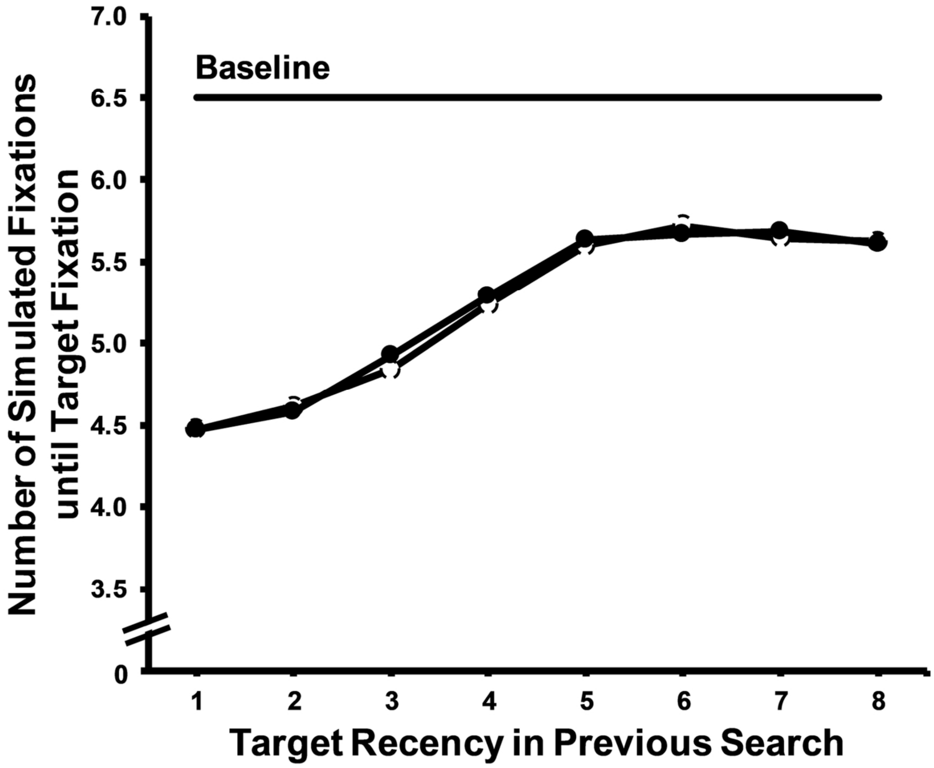


Figure 1. Summary of simulation results. (D) Number of simulated fixations until target fixation in Search 2 (dashed line) and Search 3 (solid line), depending on the target recency in the previous search. The baseline indicates the mean number of fixations until first target fixation in Search 1.

152x124mm (300 x 300 DPI)

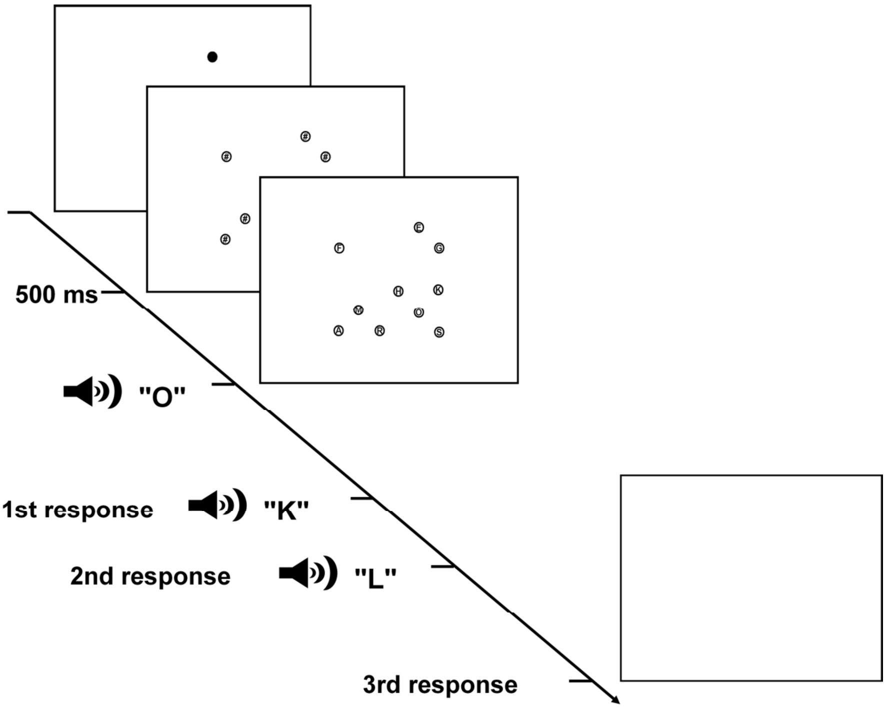


Figure 2. Sequence of events in a trial.

180x131mm (300 x 300 DPI)

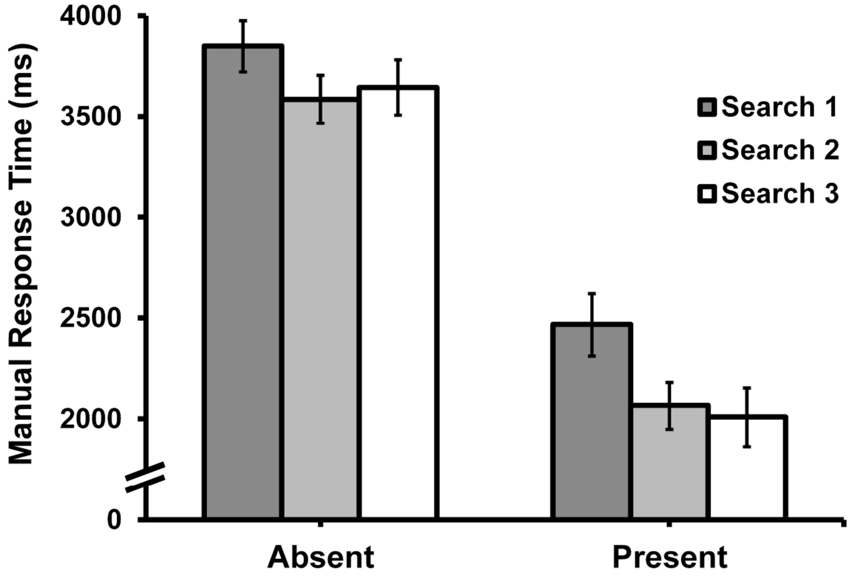


Figure 3. Mean response times for the three consecutive searches, separately for target-absent and target-present searches. Error bars represent the 95% confidence intervals (Cousineau, 2005; Morey, 2008).

144x108mm (600 x 600 DPI)

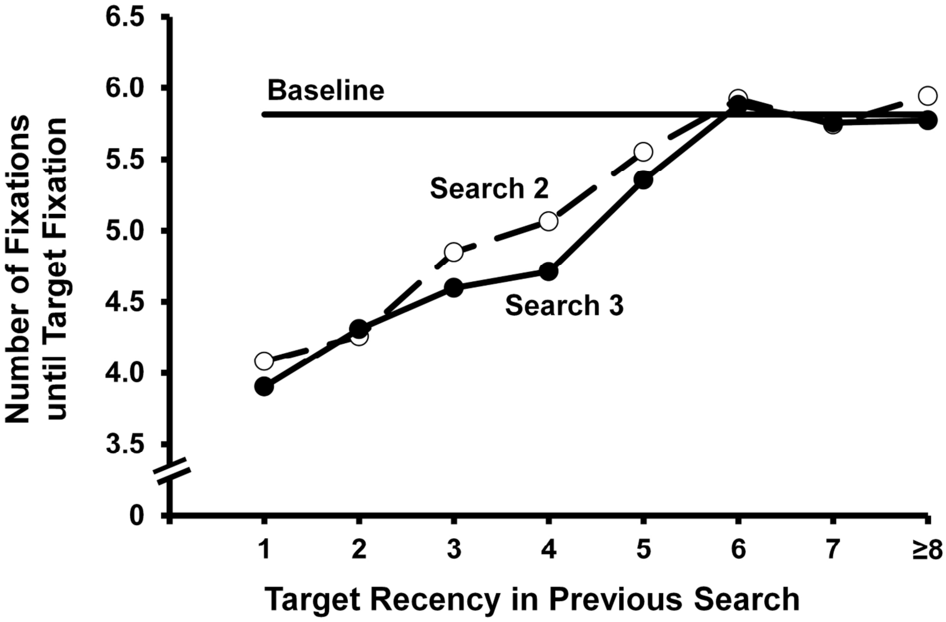


Figure 4. Number of fixations until the first target fixation in Search 2 (dashed line) and Search 3 (solid line), depending on the target recency in the previous search. The baseline indicates the mean number of fixations until first target fixation in Search 1. Search 2 performance was better than baseline for recency positions 1, 2, 4, and Search 3 performance was better than baseline for positions 1 to 4.

112x76mm (600 x 600 DPI)

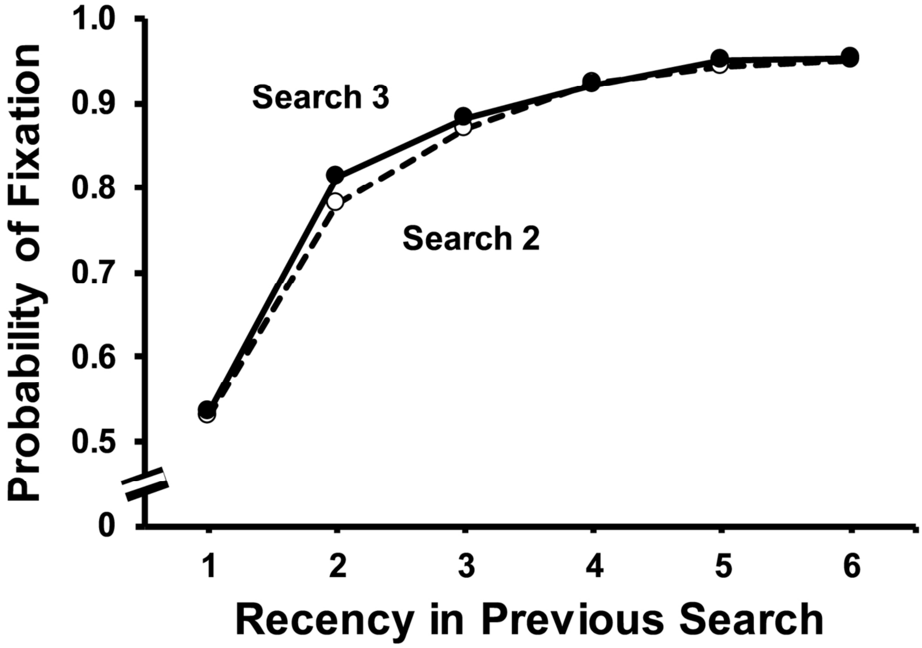
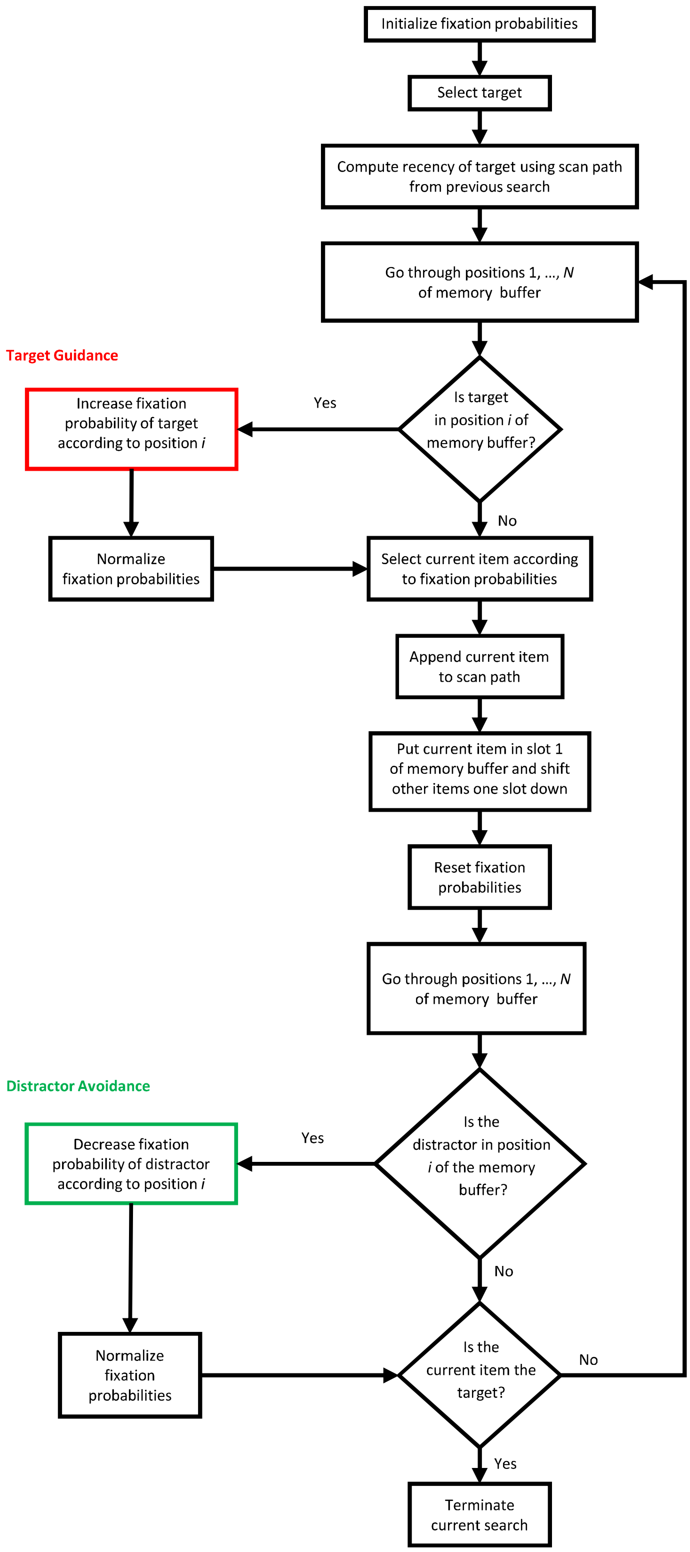


Figure 5. Probability for an item to be fixated in Search 2 (dashed line) and Search 3 (solid line) in target-absent searches, depending on its recency in the previous search.

87x62mm (600 x 600 DPI)


Initialize fixation probabilities
Select target
Compute recency of target using scan path from previous search
Go through positions 1, ..., N of memory buffer
Target Guidance
Is target in position i of memory buffer?
Yes
Increase fixation probability of target according to position i
No
Normalize fixation probabilities
Select current item according to fixation probabilities
Append current item to scan path
Put current item in slot 1 of memory buffer and shift other items one slot down
Reset fixation probabilities
Go through positions 1, ..., N of memory buffer
Distractor Avoidance
Is the distractor in position i of the memory buffer?
Yes
Decrease fixation probability of distractor according to position i
No
Normalize fixation probabilities
Is the current item the target?
No
Yes
Terminate current search